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relevant to Ontario's policy directions for emulating natural disturbance

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Abstract

This review of the literature is focused on establishing the state of knowledge on post-fire residuals as relevant to directions in Ontario's *Forest Management Guide for Natural Disturbance Pattern Emulation*. The post-fire residuals addressed here include live residuals (patches of live trees and individual live trees) as well as dead residual structure (snags and downed wood) remaining following forest fires. We review the descriptions, definitions and classification of residuals; estimates of their abundance and variability; and their spatial associations and temporal trends as reported for boreal North America, captured from reports that are published and universally accessible. Overall, the body of literature is relatively rich in terms of the number of publications that report estimates of abundance and extent of post-fire residuals. However, because the approaches used in defining and quantifying residuals are inconsistent, and sometimes ambiguous, it is difficult to synthesize and generalize this information. Furthermore, information on methods and results, which is critical to determine general patterns and trends in residuals, is relatively poor. Therefore, it is difficult to synthesize the published knowledge and generalize on abundance and variability of post-fire residuals, especially in relation to causal mechanisms, spatial associations, and temporal changes. While this is the largest gap in published knowledge of post-fire residuals, it is also the area of scientific knowledge most required for translating broad forest policies for emulating natural disturbances into specific forest management directions and practices.

Resumé

Cette étude de la documentation vise à établir l'état actuel des connaissances sur les résidus après incendie, conformément aux directives énoncées dans le guide ontarien *Forest Management Guide for Natural Disturbance Pattern Emulation*. Les résidus après incendie dont il est ici question désignent les résidus vivants (carrés d'arbres vivants et arbres vivants isolés) autant que les structures résiduelles mortes (chicots et bois au sol) qui subsistent après un feu de forêt. À partir de rapports publiés et accessibles au grand public, nous étudierons la description, la définition et la classification des résidus, l'estimation quant à leur abondance et à leur variabilité, ainsi que les associations spatiales et les tendances temporelles telles que publiées pour la forêt boréale d'Amérique du Nord. Dans l'ensemble, les publications qui proposent des estimations de l'abondance et de l'étendue des résidus après incendie s'avèrent relativement nombreuses. Cependant, les méthodes utilisées pour définir et quantifier les résidus étant contradictoires, voire ambiguës, il est difficile de colliger et de généraliser ces renseignements. En outre, l'information concernant les méthodes et les résultats, essentielle pour dégager des modèles et des tendances générales en matière de résidus, est relativement pauvre. Il est donc difficile de faire la synthèse des données publiées et de tirer des conclusions sur l'abondance et la variabilité des résidus après incendie, particulièrement en ce qui concerne les mécanismes causaux, les associations spatiales et les changements temporels. S'il s'agit là de la plus importante lacune dans le spectre des publications sur les résidus après incendie, c'est également un sujet de connaissances scientifiques indispensable pour interpréter les politiques forestières générales et pour permettre que les perturbations naturelles servent d'inspiration dans la rédaction de certaines directives et pratiques d'aménagement forestier.

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David Andison, Greg Lucking, Doug McRae, and Roger Suffling reviewed and refined the questions developed as a base for extracting information from the literature. Jim Baker, Mike Brienesse, Joe Churcher, Michael Drescher, Brian Naylor, and Bruce Ranta reviewed the draft of this report and helped improve its content and clarity. Abigail Obenchain provided editorial assistance.

Contents

INTRODUCTION

Why the interest in residuals?

Even the most intense forest fires do not reduce an entire burned area to ash. Fire intensity within forest fires varies as weather and site conditions change, leaving live forest patches, and individual trees, as well as dead structure as standing trees and downed stems. Such remnant structure from pre-burn forests are collectively known as post-fire *residuals.* These are known or expected to have various roles in the ecological function of the post-fire ecosystem, from providing a propagule source for regenerating a new forest and thus enhancing forest reestablishment and species diversity to providing structural diversity and thus habitat for wildlife, to retaining *in situ* site nutrient pool and thus long term forest productivity. Therefore, it is believed that retaining residuals during forest harvest, similar to forest composition and structure created by natural fire disturbance, helps to sustain forest ecological processes and thus conserve biodiversity (Hunter 1990).

Given the paradigm shift to emulating natural forest disturbances as a formal forest management goal, knowledge of post-fire residual structure has become an important aspect in planning forest harvests. This is especially evident in Canada, where various formal approaches have been adopted for retaining unharvested forest structure as post-harvest residuals to meet natural disturbance emulation goals. For example the province of British Columbia has set guidelines for stand structure retention during forest harvest specified by biogeoclimatic zones (BCMF 1995), and research is underway to improve application of these guidelines (DeLong 2007). In Alberta, each forest management plan has targets for retaining a combination of single stems, clumps, and islands of residuals in harvest areas, which vary with management objectives (ASRD 2006). The province of Quebec is also developing residual retention guidelines for forest management (Jette 2007).

In Ontario, emulating natural forest disturbances is a principle in the *Crown Forest Sustainability Act* (Statutes of Ontario 1995), leading to development of forest management policies that guide forest harvest practices based on natural disturbance patterns. The *Forest Management Guide for Natural Disturbance Pattern Emulation* (NDPE guide, OMNR 2001), applied in Ontario since 2003, specifies standards, directions, and guidance to emulate fire disturbances during forest harvest, including the amount of residual structure to retain. It directs forest managers to leave specific amounts of residual structure as live tree patches, individual live trees, and snags and an unspecified amount of downed woody material during timber harvesting (OMNR 2001).

In 2003, the Ontario Ministry of Natural Resources (MNR) was requested to assess the effectiveness of the directions provided in the NDPE guide (Condition 39c of the Declaration Order MNR-71 (OEAB 2003) under the *Environmental Assessment Act*). A series of research studies were initiated under this mandate to examine and reduce the uncertainties associated with the NDPE guide directions for leaving residual patches and trees as well as other emulation criteria. A complete description of the research studies and their interlinkages can be found in the study project prospectus (Perera and Buse 2006).

What is the purpose of this report?

The first step in assessing the effectiveness of the directions in the NDPE guide for post-harvest residuals is establishing the state of the scientific knowledge in the published literature on post-fire residuals. As that first step, this report documents the state of published knowledge about post-fire residuals in boreal forests of North America, specifically as relevant to Ontario's NDPE guide directions. We focussed on determining what is known in published literature about abundance, spatial and temporal variability, and distribution of post-fire residual live trees, snags, and downed woody debris. We subsequently used this information to assess the level of certainty (rigour and confidence) of the knowledge and to identify knowledge gaps. We anticipate that this state of knowledge review will also support future policy development efforts.

In this report, we present the results of the literature review, including:

- A description of the methodological steps we followed in searching, reviewing, and synthesizing literature
- Definitions and descriptions of post-fire residuals
- Abundance and variability of specific types of post-fire residual structure
- Associations of post-fire residual structure with forest cover, site conditions, and fire behaviour

We also identify knowledge gaps and uncertainties about aspects of post-fire residual structure that are relevant to the NDPE guide directions.

This report presents a review of published literature on post-fire residuals to establish the state of knowledge relevant to directions in Ontario's Forest Management Guide for Natural Disturbance Pattern Emulation. It describes post-fire residuals, their abundance and variability, and their spatial associations and temporal trends as reported for boreal North America.

METHODS

How did we search the literature?

The objective of the literature search was to locate all scientific literature on the abundance, distribution, and variability of post-fire residuals in boreal forests of North America, focused on boreal species (excluding for example, lodgepole pine (*Pinus contorta*)) as relevant to forest types in Ontario. This includes the boreal component of the transition forest (Great Lakes-St. Lawrence and Acadian forest regions, after Rowe 1972) between the eastern North American boreal and deciduous forest regions. To establish the state of knowledge of post-fire residuals in boreal forests, we reviewed published reports, guided by a hierarchical questionnaire prepared *a priori* (see Appendix I), and organized/synthesized that knowledge in relation to the directions provided in MNR's NDPE guide (OMNR 2001).

We searched for literature using a keyword list (see Appendix II), developed based on the questions formulated about uncertainties in post-fire residual structure knowledge. A search of primary databases for published literature was augmented by an *ad hoc* search of the Internet and other secondary sources.

We defined *scientific literature* as documents that report scientific analyses of data or discussions of concepts and that are readily available. These documents included journal papers, books, book chapters, graduate theses, conference proceedings, research reports, and technical reports. They had to be widely accessible, i.e., not be internal reports with restricted access; completed, i.e., not drafts or in press; have clear and repeatable methods; and ideally be peer-reviewed. We did not include web-based notes or unpublished reports.

Four categories of keywords – forest type, geographic location, disturbance type, and residual structure – were used to search several major electronic databases (TreeCD, Biological Abstracts, National Library of Canada). TreeCD was the primary source of peer-reviewed literature, and the National Library of Canada provided an archive of Canadian graduate theses titles and abstracts. The search covered literature published from 1939 (TreeCD) to December 2006. As well, an online inquiry was posted to ECOLOG-L (Ecological Society of America Listserv) to include publications in press at the time of the search.

We filtered the literature (hereafter referred to as reports) to remove duplicate information (same results published more than once) and sorted the rest based on whether the study goals were directly or indirectly related to post-fire residuals. We considered reports to be directly residual-related if the stated goal related to the study of residuals (quantitative or qualitative), and no other study goals were mentioned (for example, harvest-fire comparisons or natural disturbance emulation reports included only if residuals studied). If not (i.e., when study goals were other than residuals), then reports were considered indirectly related to residuals. These reports were further grouped into the following categories:

(a) fire behaviour

(b) harvest-fire comparison (includes salvage, wildlife)

(c) wildlife habitat in fires

(d) post-fire succession/regeneration

(e) carbon/decomposition

(f) other

We then extracted the metadata and information relating to our list of specific questions (Appendix I) from this literature and synthesized it.

What is the nature of the published literature on residuals?

The body of knowledge captured here was extracted from reports that:

- Are published and universally accessible
- Focus on boreal North American forests
- Contain a set of predetermined keywords
- Were published between 1939 and 2006

We found that these reports originate from studies on many topics other than post-fire residuals, including fire behaviour, harvest-fire comparisons, wildlife habitat in fires, post-fire succession/regeneration, and carbon/decomposition (Figure 1).

An analysis of temporal trends in the literature shows that in the first part of the current decade focus on post-fire residuals increased (Figure 2).

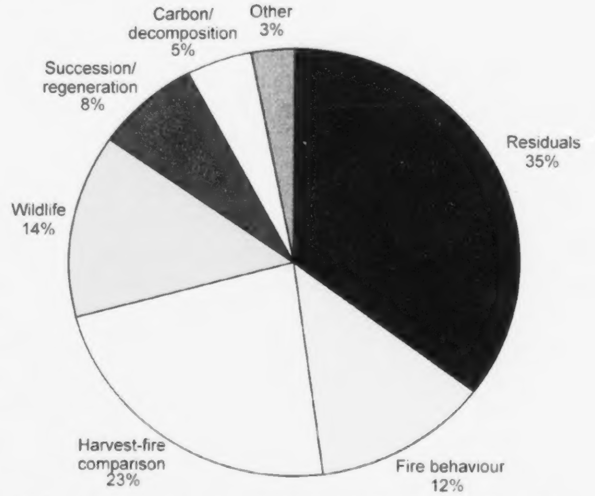


Figure 1. *Primary focus of published reports that provide information about post-fire residuals.*

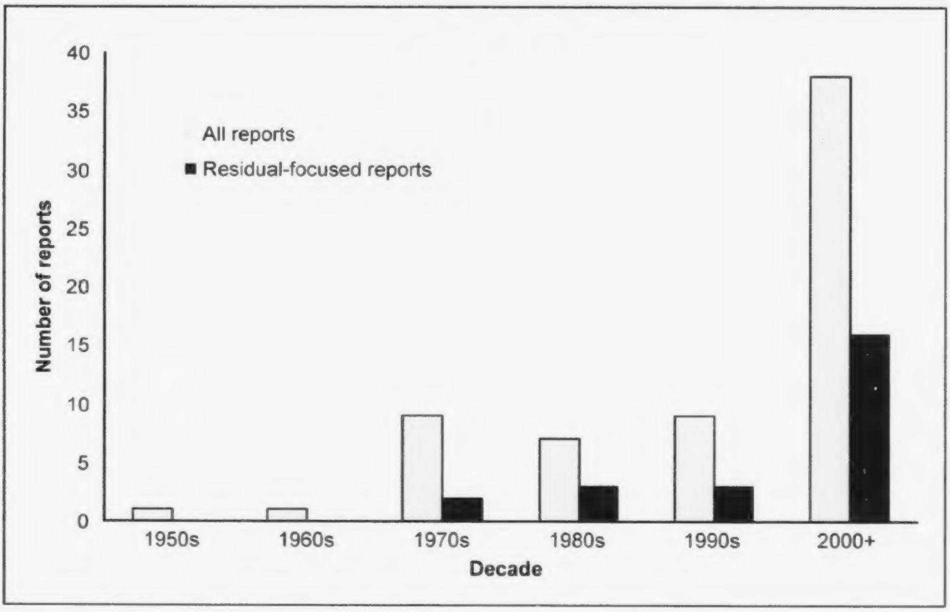


Figure 2. *Changes over time in the number of published reports containing information about post-fire residuals in the North American boreal forest (grey) and those focussed primarily on studying residuals (black) by decade.*

WHAT ARE RESIDUALS?

To assess the state of knowledge of post-fire residuals, it is important to understand how residuals are defined and described. In this section we present a summary of terms used to describe post-fire residuals in the literature, as well as descriptions for the types of residuals. We then summarize the abundance and variability of post-fire residuals reported in the literature using these categories of residuals in relation to the directions provided in Ontario's NDPE guide.

How are residuals described?

Post-fire residual structure is the part of a forest stand that did not burn to ash or gases during a fire, and is a mix of live and dead trees that form a spatial continuum, ranging from unburnt groups of live trees to single tree stems lying on the forest floor. Residual structure changes over time as trees die and fall over, and fallen trees decompose. As such, post-fire residual structure can be described generally as the remnant part of the pre-fire forest community at any given time after the fire event. Following this generic definition, residuals could be grouped and defined in a number of ways. For example, by:

1. ***Spatial contiguity of their occurrence***: Residual live trees could be grouped as single trees to aggregates (patches) of live trees, with the latter described using clustering criteria such as minimum aggregate extent and strength of aggregation.
2. ***Degree of fire damage***: Single residual trees could be grouped as unburned trees, partially burned trees, and completely burned trees.
3. ***Physiological condition***: Single trees could be grouped as live trees or dead trees (snags).
4. ***Degree of pronation***: Single trees could be grouped from upright to slanted (leaning) to downed.
5. ***Ecological value***: Single trees could be classified as habitat trees, den trees, or seed trees, depending on the value of interest.

Residuals could also be categorized and defined based on their origin, i.e., how they were formed during the fire:

- ***Escapees***: Fire did not reach them.
- ***Tolerants***: They were subjected to fire but were not affected.
- ***Resilients***: They suffered fire damage but survived.
- ***Dead***: They did not survive fire but were not reduced to ash.

In the literature, only Rowe (1983) emphasized the residual formation process as described above. Overall, the published literature does not present a consensus on descriptions, groupings, or identity of residuals. Most reports referred to and defined residuals subjectively based on a specific study goal or arbitrarily based on observations from data post hoc. The most common groupings in literature were *live tree patches*, *live* or *residual trees*, *snags* (standing dead trees), and *downed wood* (dead trees lying on the ground). This set of groupings is congruent with those used in the NDPE guide: *residual patches, individual residual live trees, snags,* and *down woody debris*. The NDPE guide further separates residual patches into *insular* and *peninsular*. The only other reference to separation of residual patches in the literature is by Larsen (1962) who contrasted peninsular patches of residuals with residual 'islands'.

Also absent in the published literature on residuals is any discussion of the relevance of scale to residual patch descriptions, even though the residual formation process (spread of forest fire and its severity) and the perception of residuals (definitions and observations) depend on spatial resolution. Furthermore, based on published reports residuals are studied and addressed either as live tree residuals or live tree patches without specifying the thresholds along the spatial continuum of individual live trees to live tree aggregates.

Table 1. *Terms used to describe/define post-fire residual structure in the published literature compared with those used in Ontario's* Forest Management Guide for Natural Disturbance Pattern Emulation *(NDPE guide) (shaded).*

Residual patches	Residual trees	Residual snags*	Downed wood*
Islands and peninsulas (Larsen 1962)	**Individual surviving trees** (Lutz 1956)	**Standing dead wood** (Methven et al. 1975, Bond-Lamberty et al. 2003)	**Above- and below-ground downed wood** (Methven et al. 1975)
Stringers (Lutz 1956, Quirk and Sykes 1971)	**Scattered trees** (Scotter 1972)	**Standing dead trees** (Ohman and Grigal 1979, Schulte and Niemi 1998, Lee and Crites 1999, Drapeau et al. 2002)	**Downed wood: includes logs and snags** (Graf et al. 2000)
Areas burned less fiercely (Methven et al. 1975)	**Remnant trees** (Ohman and Grigal 1979)	**Self-supporting standing dead trees** (Ferguson and Elkie 2003)	**Logs** (Graf et al. 2000, Harper et al. 2004)
Upland strings (Scotter 1972)	**Residual trees** (Schulte and Niemi 1998, Hobson and Schiek 1999, Kemball 2002, Lee 2002, Morissette et al. 2002, Haeussler and Bergeron 2004)	**Dead trees with no green needles** (Nappi et al. 2003)	**Downed dead wood** (Bond-Lamberty et al. 2003)
Unburned inclusions (Mychasiw 1983, Thomas et al. 1998)	**Live trees** (Imbeau et al. 1999, Stambaugh 2003)	**Residual snags of fire origin** (Awada 2004)	**Coarse woody material** (Sander 2003, Stambaugh 2003)
Unburned islands (Eberhardt and Woodard 1987)	**Live tree residuals** (Kurulok 2004)	**Standing ash-covered snags** (Capar 2004)	**Wind-fallen downed dead wood** (Hauessler and Bergeron 2004)
Live tree patches (Shieck and Hobson 2000)		**Residual snags of fire origin** (Awada 2004)	**Ash-covered snags on ground** (Capar 2004)
Unburned patches (Nowak et al. 2002)		**Standing ash-covered snags** (Capar 2004)	**Not rooted** (Kurulok 2004)
Live tree residuals (Lee and Smyth 2003)			**Boles and branches** (Lavoie 2004)
			Logs and stumps (St. Germaine 2004)
NDPE guide (OMNR 2001)			
Insular residual patch *Peninsular residual patch*	*Individual residual live trees*	*Snags*	*Downed woody debris*

* implies that snags and downed wood are those created by fire, but is usually confounded with dead trees and downed wood that predate the fire event

Therefore, we adhered to the above residual groupings common in the published literature in this review, without reference to spatial scale of residual formation or observation. Furthermore, terms used to denote residuals within these broad groupings differ among authors, which may reflect their specific study goals but can lead to ambiguity and confusion during knowledge synthesis. The same term has even been used for different categories of residuals: For example, Lee and Smyth (2003) referred to patches as live tree residuals, the same term Kurulok (2004) used for individual trees. Table 1 lists the many terms used to describe post-fire residual structure in the literature by category.

Residual patches

In the published literature, areas of live trees within a forest fire are often assumed to be *live* patches, but some reports specifically mentioned degrees of greenness. For example, some specified 100% non-burned (Scotter 1972, Smyth 1999, Shieck and Hobson 2000) or unburned (e.g., Eberhardt and Woodard 1987, Novak et al. 2002). Others were less specific, referring to greenness as partially burned (Rees and Juday 2002) or majority of trees not dead (Lee and Smyth 2003) or providing categories of tree crown scorch (Kafka et al. 2001). Ontario's NDPE guide does not mention degree of greenness in defining or describing residual patches.

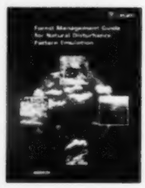
Spatial descriptions of live tree patches varied. Some referred to areas that burned *less fiercely* (Methven 1975), while others indicated spatial connotation of clustering of unburned areas as *patches* (Novak et al. 2002) or live tree patches (Shieck and Hobson 2000). In terms of shape, live tree patches were referred to as stringers (Quirk and Sykes 1971, Scotter 1972) and islands in a matrix of fire (Eberhardt and Woodard 1987). All of the above terms refer to internal patches of live trees, which are named insulars in Ontario's NDPE guide. Only few reports referred to peninsular patches as described in the NDPE guide: Larsen (1962) as peninsulas and Mychasiw (1983), and Thomas et al. (1998) as inclusions.

Some reports considered residual areas in terms of their location, i.e., they must be fire-created islands (Bergeron et al. 2002), not including natural islands such as those in lakes (Larsen 1962). In general, no clear or consistent separation is made in literature between escapees and survivors.

Minimum area classified as a patch differs widely among reports (Table 2), ranging from 0.1 ha to 1 ha. Most common minimum patch size was 1 ha, but some reports did not specify a minimum (e.g., Bergeron et al. 2002). In some reports, minimum patch size was a function of the minimum resolution of the imagery used for the study (e.g., Mychasiw 1983).

Insular and peninsular residual patch retention

Living internal patches, consisting of distinct "islands" greater than 0.25 ha, will be retained on clearcut areas to provide vertical structure, relic patches of old growth, wildlife habitat and future sources of downed woody debris. For similar reasons, portions of live peninsular patches which are connected to the harvest block perimeter will also be retained.



NDPE guide (OMNR 2001)

Table 2. *Degree of greenness and minimum patch sizes described in the published literature compared with those in Ontario's* Forest Management Guide for Natural Disturbance Pattern Emulation *(NDPE guide) (shaded).*

Residual patch descriptions/categories	
Live:dead tree ratio	**Patch size**
All green (Scotter 1972, Smyth 1999, Shieck and Hobson 2000) **Three categories of crown scorch: none; green>scorched; green<scorched** (Kafka 2001) **<75% canopy mortality** (Lee and Smyth 2003) **Partially burned inclusions** (Rees and Juday 2002) **Unburned** (Mychasiw 1983, Eberhardt and Woodard 1987, Thomas et al. 1998, Nowak et al. 2002)	***Insular*** **Small** (Scotter 1972, Novak et al. 2002) **≥1 ha** (Eberhardt and Woodard 1987, Kafka 2001) **≥1 ha and ≥20 m wide** (Smyth 1999) **Small patches (<10 ha) and large patches (> 100 ha)** (Shieck and Hobson 2000) ***Peninsular*** **<400 m base for fires <260 ha and 400-1000 m for fires >260 ha** (Perron 2003, based on OMNR 2001)
NDPE guide definitions (OMNR 2001)	
Not specified	***Insular*** *>0.25 ha* ***Peninsular*** *<400 m base for fires <260 ha and 400-1000 m for fires >260 ha*

Residual trees

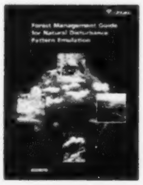
Live tree residuals were reported infrequently in the literature and were referred to mainly as live trees but also as live stems (Imbeau et al. 1999), individual surviving trees (Lutz 1956), and remnant trees (Ohman and Grigal 1979). What live tree means is often not specifically defined, although one report defined *greenness* for live tree residuals by the percent of foliage browning: <25%, 25-49, 50-74, and >75 (Beverly and Martell 2003). As well, origin of live tree residuals – escapees, tolerants, survivors (*sensu* Rowe 1983) – was not specifically indicated in literature. However, origin of residuals was sometimes inferred in generalized post-hoc observations, e.g., the residuals were said to be located in wet, poorly drained, low, or lightly burned areas.

A range of diameter (>2 cm to >20 cm) and height (>1.3 m to >5 m) limits were used to categorize live tree residuals. However, other metrics, such as percent cover (Morissette et al. 2002), were also used, making comparisons among studies difficult (Table 3). For live trees, size specifications were not differentiated by species.

Individual residual trees

The density and choice of individual living trees by species left on a site will be based on fire tolerance, silvicultural requirements and wildlife habitat value and the number of dead (snag) trees that were able to be left given the Occupational Health and Safety Act.

Fire tolerance: balsam fir < upland spruce/jack pine < lowland spruce < poplar/hard maple/ beech/oak < white pine/red pine (only when superdominants)



Operations should leave a minimum average of 25 well-spaced trees/ha of which at least 6 must be large-diameter, live, high quality cavity trees or those with future potential to form cavities such as large trembling aspen or hard maple....

NDPE guide (OMNR 2001)

Table 3. *Definitions for residual tree size presented in the published literature compared with those used in Ontario's* Forest Management Guide for Natural Disturbance Pattern Emulation *(NDPE guide) (shaded).*

Residual tree categories	
Diameter	**Height**
>2 cm (Hansen 1983)	**≥1.3 m** (Hauessler and Bergeron 2004, Kurulok 2004)
>2.5 cm (Apfelbaum and Haney 1981)	**2 m** (Graf et al. 2000)
>5 cm (Harper 2004, Kurulok 2004)	**≥5 m** (Imbeau et al. 1999)
>10 cm (Simon et al. 2002, Ferguson and Elkie 2003)	
≥20 cm (Imbeau et al. 1999, Harper 2003)	
Canopy and subcanopy (Hely 2000)	
NDPE guide definitions (OMNR 2001)	
a range of diameters (>10 cm)	*>3 m*

Residual snags

In the literature, snags or standing dead residuals were referred to as residual snags (Awada 2004), standing dead wood (Methven 1975, Bond-Lamberty et al. 2003), standing dead trees (Ohman and Grigal 1979, Schulte and Niemi 1998, Lee and Crites 1999, Drapeau 2002), self-supporting standing dead trees (Bishop 1998, Ferguson and Elkie 2003), dead trees with no green needles (Beverly and Martell 2003, Nappi et al. 2003), standing ash-covered snags (Capar 2004), and fire-killed trees (St. Germaine 2004).

Only two reports defined snags, as dead trees with no green needles (Beverly and Martell 2003, Nappi et al. 2003), and only two reports separated fire-killed trees from pre-fire snags (Awada 2004, Capar 2004). The amount of information about what happens to snags – decay categories, fail rates – indicates a high level of interest in this topic, but most reports focused on habitat issues rather than direct study of post-fire residual abundance and variability.

As with live trees, a range of diameter sizes (>1 cm to ≥20 cm) and height limits (>0.5 m to >4 m) are used to categorize snags, making comparisons among studies difficult. Most reports use >10 cm diameter (Table 4).

Snags

A minimum of 6 large, living potential cavity trees and 19 others (in order of preference: snags, dying trees, and living trees of varying species and sizes >10 cm in diameter and >3 m in height) will be left on all sites.

NDPE guide (OMNR 2001)

Table 4. *Definitions for snag size presented in the published literature compared with those used in Ontario's* Forest Management Guide for Natural Disturbance Pattern Emulation *(NDPE guide) (shaded).*

Residual snag categories	
Diameter	**Height**
>1 cm (Bond-Lamberty et al. 2003)	**>0.5 m** (Miyanishi and Johnson 2002, Harper 2004)
>2 cm (Hansen 1983)	**>1.3 m** (Drapeau 2002, Haeussler and Bergeron 2004)
>2.5 cm (Apfelbaum and Haney 1981)	**>1.5 m** (Kurulok 2004)
>5 cm (Schulte and Niemi 1998, Nappi et al. 2003, Harper 2004)	**>2 m** (Imbeau et al. 1999, Nappi et al. 2003)
	>3 m (Ferguson and Elkie 2003)
>10 cm (Lee et al. 1997, Lee and Crites 1999, Simon et al. 2002, Ferguson and Elkie 2003, St. Germaine 2004)	**>4 m** (Awada 2004)
>12 cm (Stambaugh 2003, Stepnisky 2003)	
>15 cm (Imbeau et al. 1999)	
≥20 cm (Harper 2003)	
NDPE guide definitions (OMNR 2001)	
>10 cm	*>3 m*

Downed wood

The published literature presented many terms for describing post-fire downed wood, varying from downed dead wood (Bond-Lamberty et al. 2003, Haeussler and Bergeron 2004) to coarse woody debris (Graf et al. 2000) or coarse woody material (Sander 2003, Stambaugh 2003) to logs (Graf et al. 2000, Harper et al. 2003, 2004, St. Germaine 2004) and ash-covered snags on the ground (Capar 2004). While Kurulok (2004) specified that downed wood is not rooted, others included both snags and downed wood as dead wood (Graf et al. 2000), and one report included stumps as well (St. Germaine 2004). Where snags were included as downed wood, sometimes a minimum angle of <45° is specified; i.e., those likely to fall (Bishop 1987). Some reports included boles and branches in downed wood assessments (Hely 2000, Lavoie 2004).

Downed wood descriptions and categories were also inconsistent (Table 5). For example, the minimum sizes included in assessments ranged in diameter from >1 cm (Bond-Lamberty et al. 2003) to >10 cm (St. Germaine 2004), with >5 cm most common (Hobson and Schieck 1999, Lee and Crites 1999, Sander 2003, Harper 2004, Haeussler and Bergeron 2004, Kurulok 2004). Less often a minimum length was reported, e.g., >50 cm (Kurulok 2004). In one report, downed wood size specifications varied by species (Sander 2003).

Table 5. *Definitions for downed wood size presented in the published literature compared with those used in Ontario's* Forest Management Guide for Natural Disturbance Pattern Emulation *(NDPE guide) (shaded).*

Downed wood categories		
Diameter	**Length**	**Other**
>1 cm (Bond Lamberty et al. 2003)	**>50 cm** (Kurulok 2004)	**<45° angle from ground** (Bishop 1987)
>5 cm (Hobson and Shieck 1999, Lee and Crites 1999, Sander 2003, Haeussler and Bergeron 2004, Harper 2004, Kurulok 2004)		**Pine and aspen given different specifications** (Sander 2003)
5 classes below 7 cm and one 7 cm+ (Hely 2000, Lavoie 2004)		**Percent cover** (Schulte and Niemi 1998, Morissette et al. 2002)
>8 cm (Stambaugh 2003)		
>10 cm (St. Germaine 2004)		
>1-2; 2-10; 10+ cm classes (Hansen 1983)		
NDPE guide definitions (OMNR 2001)		
Not specified	*Not specified*	*Provide coarse downed woody debris*

How much is left behind? Abundance and variability of residuals

Residual patches

Abundance of live tree patches was reported several ways in the literature, with most reporting it as the proportion of fire area that did not burn (Mychasiw 1983, Gluck and Rempel 1996, Thomas 1998, Thomas et al. 1998, Smyth 1999, Kafka et al. 2001, Bergeron et al. 2002, Perron 2003). Others reported the number of patches per hectare of fire (Eberhardt and Woodard 1987, Gluck and Rempel 1996, Smyth 1999, Kafka et al. 2001, Perron 2003). Fewer reports provided mean patch area or patch size estimates (Eberhardt and Woodard 1987, Gluck and Rempel 1996, Kafka et al. 2001, Stewart 2004). One report specifically assessed the amount of patch area per kilometre of stream in riparian areas only (Lee and Smyth 2003).

The proportion of internal residual patches (islands) in forest fires as reported in the published literature ranged from none to 17% (Mychasiw 1983, Eberhardt and Woodard 1987, Smyth 1999, Bergeron et al. 2002, Perron 2003). We graphed reported values of forest fire sizes and their respective insular residual areas (Figure 3) on a log-log scale to illustrate their distribution. An important note is that these reports of residual patches did not use the same definition for patches; minimum patch sizes were < 1 ha (Mychasiw 1983, Perron 2003), ≥1 ha (Eberhardt and Woodard 1987, Smyth 1999), or undefined (Bergeron et al. 2002).

Number of live tree patches reported varied from none (Eberhardt and Woodard 1987, Kafka et al. 2001) to 10.4 patches per 100 ha of fire area (Gluck and Rempel 1996). Two reports indicated that the number of live tree patches varies with fire size; for example, Perron (2003) reported fires less than

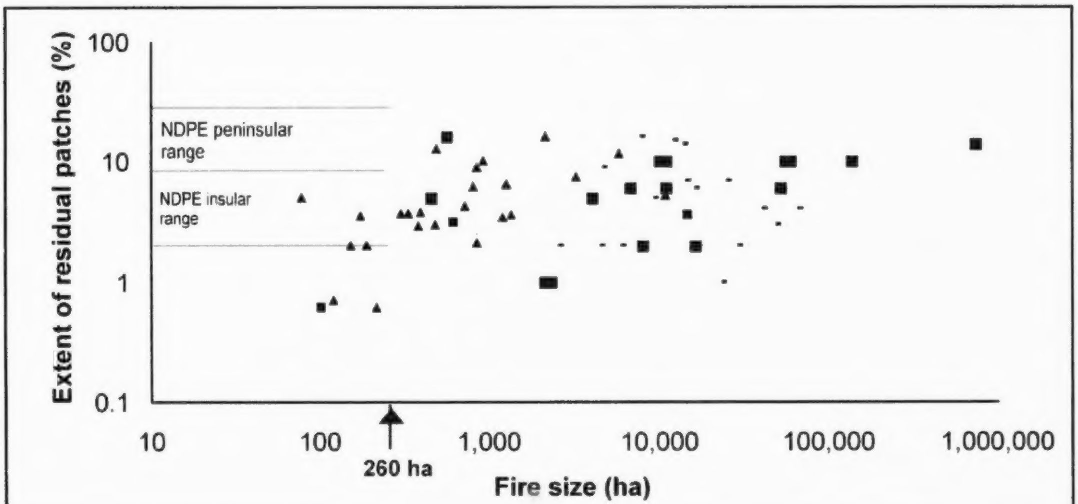


Figure 3. *Proportion of unburned area in island residuals relative to total fire size as reported in the published literature (data from Mychasiw 1983, Eberhardt and Woodard 1987, Smyth 1999, Bergeron et al. 2002, Perron 2003). Symbols are: ■ = minimum patch size <1 ha; ▲ = minimum patch size ≥1 ha; – = minimum patch size not specified.*

(Note: The range specified in Ontario's Forest Management Guide for Natural Disturbance Pattern Emulation *(NDPE guide) for insular and peninsular residual proportion during forest harvest is shown by the solid lines. Note that this is for comparison purposes only because NDPE guide directions for forest harvest are that 80% (by frequency) of boreal forest clearcuts must be less than 260 ha.)*

200 ha had 0 to 11 patches per 100 ha, fires 200 to 1,000 ha had 3 to 13.5 patches per 100 ha, and fires larger than 1,000 ha had 1 to 16.6 patches per 100 ha (Table 6). However, the abundance values presented in various reports could not be readily compared because patch definitions and assessment methods varied widely.

The size of live tree patches is reported to vary and can be as large as 43 ha (Kafka et al. 2001), but most reports cited maximum patch sizes of less than 10 ha (Eberhardt and Woodard 1987, Gluck and Rempel 1996). Some reports indicated that the size of live tree patches increased as fire size increased (e.g., Eberhardt and Woodard 1987). Graphing the published values supports that finding when the numbers are compared directly. However, mean patch size as a proportion of fire size decreased as fire size increased (Figure 4). Thus, while larger fires may produce larger residual patches, those patches will cover proportionately less of the fire area.

Ontario's NDPE guide specifies leaving 2 to 8% of planned disturbance area in insular residual patches based on forest cover type, with a minimum patch size of 0.25 ha and these patches are to be well distributed within the harvest area. As well, based on forest cover type 8 to 28% of planned disturbance areas is to be left as peninsular residuals that are well distributed around the edge of the harvest area. The guide also specifies that the likelihood of cover type being left as residual should be a gradient from 10% for upland conifers to 36% for tolerant hardwoods, with white pine (*Pinus strobus* L.)/red pine (*Pinus resinosa* Ait.), Great Lakes-St. Lawrence mixedwood, conifer lowlands, boreal mixedwoods, and intolerant hardwoods in between (OMNR 2001).

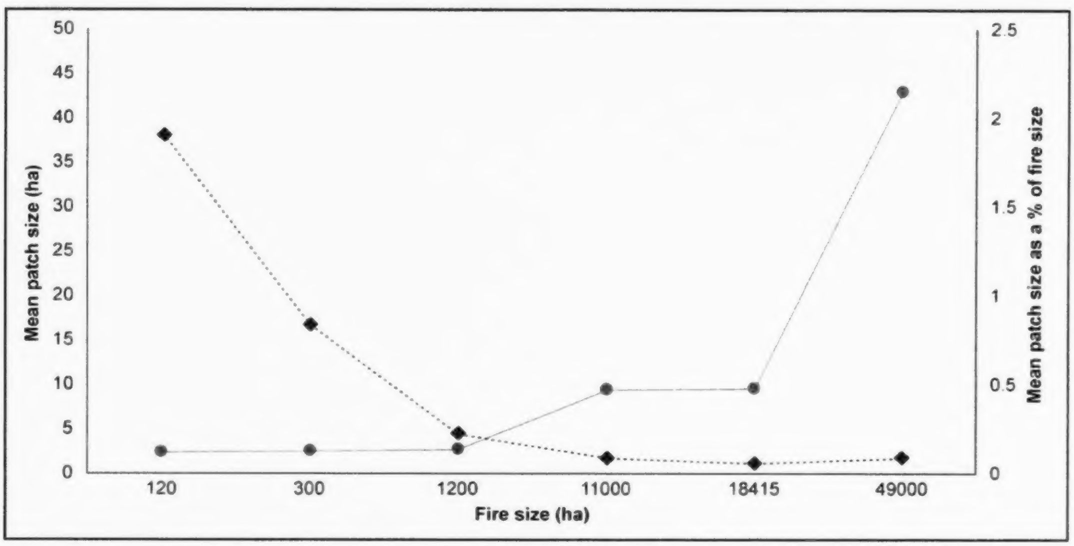


Figure 4. *Mean patch size (-●-) and mean patch size as a proportion of fire size (-◆-) by fire size as reported in the published literature (data pooled from Eberhardt and Woodard 1987, Gluck and Rempel 1996, Kafka 2001).*

Table 6. *Live tree patch extent, abundance, and size reported in the literature by study location and fire size.*

Proportion of fire area in patches (mean)	Patches per 100 ha (mean)	Mean area of patches (ha)	Mapping unit	Location	Study fires (#)	Fire size (ha)	Citation
1-16% (7)	–	–	<1 ha	Northwest Territories (NWT)	17	1,822 - 755,602	Mychasiw 1983
0-5.2%	0-1	2.3-9.4	≥1 ha	Alberta	69	21-17,770	Eberhardt and Woodard 1987
21% total	10.4	9.6	–	Ontario	1	18415	Gluck and Rempel 1996
<5%	–	–	–	Manitoba, Saskatch-ewan, NWT	–	–	Thomas et al. 1998
0.6-16%	0.5-3.8	–	1 ha	Alberta	20	77 - 5,765	Smyth 1999
2-6%	–	43	–	Quebec	1	49070	Kafka et al. 2001
1.5-17% (5)	–	–	–	Quebec	16	4509-66,655	Bergeron et al. 2002
0-8% insular 7-37% total	0-11 (4) (<200 ha fires) 3-13.5 (8.5) (200-1000 ha) 1-16.6 (6) (>1000 ha)	–	0.1 ha	Quebec	35	35-29,683	Perron 2003

– = not reported

Residual trees

The published literature reported a range of live tree abundance values, mostly as number of stems per hectare, ranging from none (Viereck and Dyrness 1979, Imbeau 1999, Kurulok 2004) to 10s (Stuart-Smith et al. 2002) to 100s (Viereck and Dyrness 1979, Schulte and Niemi 1998, Stambaugh 2003, Harper et al. 2004). Live tree abundance is reported less often as basal area per hectare, ranging from none (Haeussler and Bergeron 2004) to 50 m^2/ha (Apfelbaum and Haney 1981) (Table 7).

Reported live tree abundance values were few and highly variable and may depend on the methods used to obtain them (Figure 5). Project objectives may influence sampling approaches and thus reported abundance. For example, Harper et al. (2004) specifically sampled transects across fire edges and excluded fire interior. As well, as noted in Table 3, reported studies applied different minimum sizes for live trees, which likely affected numbers reported.

Timing of sampling, i.e., immediately versus a few years post-fire, may also affect reported abundance due to live tree mortality and tree and snag fall. We present only abundance values reported within five years of the fire. However, since most live tree mortality was reported to occur within that timeframe (see section on longevity of residuals), abundance values will be affected by time since fire.

Residual abundance may vary by forest cover type due to difference in species fire tolerance (Scotter 1972). For example, many reports indicated that no residuals remained in aspen (*Populus* spp.)-dominated mixedwoods after fire; however, most reports indicated that some residuals remained in black spruce (*Picea mariana* Mill. BSP) stands (Table 7). While Schulte and Niemi (1998) reported that two years post-fire in an aspen-dominated mixedwood in Minnesota, 59% of residuals were conifers and only 11% aspen. However, without prefire information, it's uncertain whether the stand had more conifers to begin with or more conifers survived, making it difficult to link the cover type and survival information.

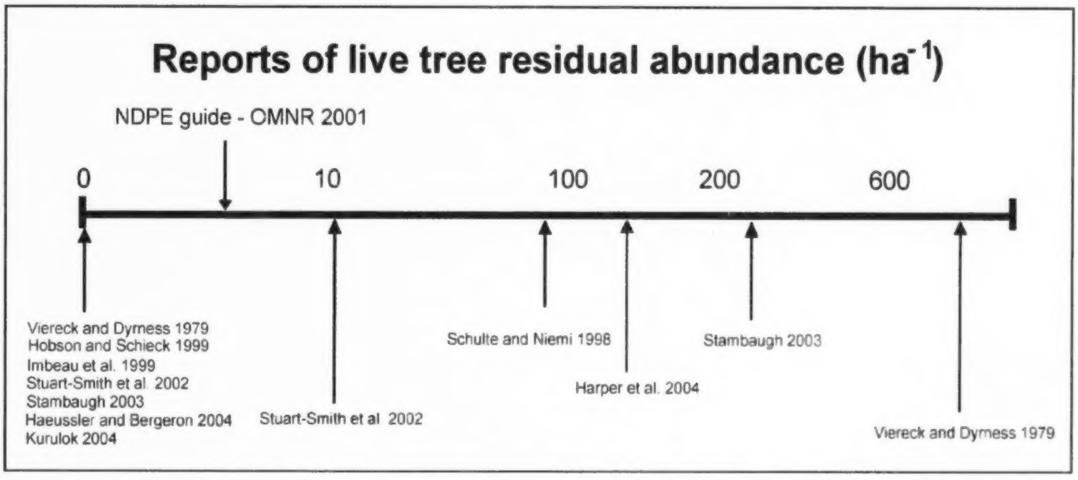


Figure 5. *Live tree residual abundance (number per hectare) within five years post-fire as reported in the published literature relative to directions in Ontario's* Forest Management Guide for Natural Disturbance Pattern Emulation *(NDPE guide). These estimates cannot be directly compared given different forest cover types, site conditions, fire characteristics, and time since fire but they do indicate the variability in post-fire live tree residuals.*

Given the few abundance values reported in the published literature and the very different conditions under which these values were generated, they cannot be readily compared or generalized. Key information needed to compare live tree abundance estimates among studies includes pre-burn stand characteristics (cover type, age, size, density), fire characteristics, time since fire, and site variables.

Ontario's NDPE guide specifies leaving a minimum of 25 stems per hectare as a combination of live trees and snags of varying species and sizes (OMNR 2001).

Table 7. *Reported live tree abundance 5 years post-fire in North American boreal forests by forest cover type.*

Abundance: Density (stems/ha)	Abundance: Basal area (m^2/ha)	Location	Fires studied (#)	Fire information	Years post fire	Cover type	Site type	Citation
0	–	Alberta	–	–	1	Aspen-dominated mixedwood	–	Hobson and Schieck 1999
0	–	Alberta	3	May-July 3801-7207 ha	2	Aspen-dominated mixedwood	–	Kurulok 2004
0	0-12	Ontario	4	Crown fire May-June 204-3538 ha	3	Aspen-dominated mixedwood	–	Haeussler and Bergeron 2004
97	–	Minnesota	1	May 2100 ha	2-3	Aspen-dominated mixedwood	–	Schulte and Niemi 1998
0-10.4	–	Alberta	1	June 3600 ha	5	Mixedwood	Varied: jack pine on sand, black spruce on bog, aspen/white spruce on deep rich soils	Stuart-Smith et al. 2002
0-225	–	Alberta	1	May 14000 ha	1-3	Mixedwood	–	Stambaugh 2003
–	50.8	Minnesota	1	August	1	Jack pine/black spruce	–	Apfelbaum and Haney 1981
0	–	Alaska	1	Heavy burn	1-2	Black spruce	Ridge top/lower slope	Viereck and Dyrness 1979
0	–	Quebec	–	–	Recent	Black spruce	–	Imbeau et al. 1999
120	–	Quebec	2	–	3-4	Black spruce	Organic/clay	Harper et al. 2004
627	–	Alaska	1	Light burn June 6313 ha	1-3	Black spruce	Lower slope	Viereck and Dyrness 1979

– = not reported

Residual snags

The published literature presented a range of metrics for reporting snag abundance with most using density (number of stems per ha) and basal area (m^2 per ha) to report abundance but one report citing volume (Bond-Lamberty et al. 2003) and another number per length of transect (Graf et al. 2000). This inconsistency makes among-study comparisons difficult.

No reports cited a complete absence of snags, indicating that some residual structure always remains after fire. Post-fire snag abundance is reported as varying from as few as 57 to as many as 2,400 snags per hectare, with the widest range reported for black spruce. The latter may reflect differences in snag abundance on upland versus lowland spruce sites. Basal area values varied from 3 m^2 per hectare to 35 m^2 per hectare (Table 8). However, changing the minimum diameter of the stems included as snags (see Table 4) will affect these estimates.

No published reports related post-fire snag abundance to pre-fire stand density, so it is unclear what proportion of snags were fire caused. And as with residual trees, the paucity of information, variability in definitions, lack of documentation of pre-fire forest cover characteristics, and inconsistency in sampling

Table 8. *Reported post-fire snag abundance in North American boreal forests by forest cover type.*

Abundance								
Density (stems/ha)	Basal area (m^2/ha)	Location	Fires studied (#)	Fire information	Years post fire	Cover type	Site type	Citation
125-700	–	Alberta	1	–	1	Aspen	–	Lee and Crites 1999
–	23	Ontario	4	Crown fire May-June 204-3,538 ha	3		–	Haeussler and Bergeron 2004
263	–	Ontario	–	–	10-40		Well-drained	Ferguson and Elkie 2003
419	–	Saskatchewan	–	–	<1 +	Mixedwood	Gray luvisols	Awada et al. 2004
1,968	–	Alberta	3	May-July 3,801-7,207 ha	2		–	Kurulok 2004
–	9.7-35.5	Alberta	–	–	1		–	Hobson and Schieck 1999
754-2184	–	Quebec	–	–	11		Upland and lowland	Le Goff and Sirois 2004
1,300-1,700		Maine	1	July 1,439 ha	1	Jack pine/ black spruce	–	Hansen 1983
–	23-34	Northwest Territories	–	–	1+		Well-drained lacustrine	Lavoie 2004
57.5	–	Quebec	–	–	2		–	Larivee 2003
675	–	Quebec	–	–	Recent		–	Imbeau et al. 1999
600-2,400	–	Ontario/ Quebec	1	–	<50	Black spruce	–	Harper et al. 2005
1,710	–	Quebec	2	–	3-4		Organic/ clay	Harper et al. 2004
–	3-13	Quebec	–	–	1		–	Drapeau et al. 2002

– = not reported

approaches do not lend themselves to generalizing reported abundance values. Key information needed to compare abundance estimates among studies includes pre-burn stand characteristics and snag abundance, fire characteristics, time since fire, and site variables.

Ontario's NDPE guide specifies leaving a minimum of 25 stems per hectare as a mixture of live trees and snags of varying species and sizes (OMNR 2001).

Downed wood

The published literature contained a range of abundance values for downed wood, with most reports using volume (m^3/ha), fewer reporting percent cover, and even fewer reporting pieces per length of transect, mass, or logs per hectare. Abundance values ranged from a low of 14.1 m^3/ha in black spruce to 322 m^3/ha in mixedwood and from 0.2% cover in jack pine (*Pinus banksiana* Lamb.) /black spruce forest to 43.5% in an aspen forest (Table 9). As with snags, the relationship between abundance of post-fire downed wood and pre-fire stand and site conditions was not reported, so no information is available on the quantity of downed wood the fire generated. In addition to stand and site variables, key information needed to compare downed wood abundance estimates among studies includes pre-burn downed wood abundance, fire information, and time since fire.

Ontario's NDPE guide does not specify how much downed wood to leave when harvesting but does provide direction to leave coarse woody debris on all sites and fine woody debris on shallow or very coarse-textured sites by modifying silvicultural practices (OMNR 2001).

Table 9. *Reported post-fire downed wood abundance in North American boreal forests by forest cover type.*

Abundance		Location	Study fires (#)	Fire information	Years post-fire	Cover type	Site type	Citation
Volume (m^3/ha)	Cover (%)							
80-170	–	Alberta	1	–	1	Aspen	–	Lee and Crites 1999
–	43.5	Saskatchewan	1	Summer 40,000 ha	3		Loamy	Morissette et al. 2002
63.7	3.8	Alberta	3	May-July 3,801-7,207 ha	2	Mixedwood	–	Kurulok 2004
130	–	Ontario	1	5,000 ha	1		Sand	Pedlar et al. 2002
162.3	–	Manitoba	2	May 24,268-37,000 ha	10-13		–	Kemball 2002
232-322	–	Alberta	–	–	1		–	Hobson and Schieck 1999
–	32.9	Saskatchewan	1	Summer 40,000 ha	3		Loamy moist	Morissette et al. 2002
–	0.2-1.6	Quebec	–	–	2	Jack pine/black spruce	–	Larivee 2003
–	1-2.2	Maine	1	July 1,439 ha	1		–	Hansen 1983
–	19.8	Saskatchewan	1	Summer 40,000 ha	3		Sandy	Morissette et al. 2002
125-240	–	Ontario/Quebec	1	–	<50	Black spruce	–	Harper et al. 2005
–	5.65-7.03	Manitoba	–	–	1, 15		–	Capar 2004

– = not reported

WHY ARE RESIDUALS THERE?

Beyond the abundance and extent of residuals, understanding what causes residuals helps to predict where they might occur and determine what happens to those residuals over time. In this section, we summarize the spatial associations of post-fire residuals and describe temporal changes of residuals as reported in the literature.

Spatial associations of residuals

Why is it important to understand spatial variability?

While some of the variability in reported abundance and extent may be due to differences in definitions, study methods, and approaches, it is apparent that the extent of residual patches and abundance of residual trees, snags, and downed wood do vary spatially both among and within fires. This spatial variability is the result of a series of complex interactions among fire behaviour during a forest fire event, the nature of pre-burn forest cover, and the area's geoclimate. However, the published literature on post-fire residuals did not directly report or provide evidence of these causal mechanisms. While published reports presented many estimates of residual abundance and its variability, few explained what causes those residuals or the mechanisms that form them.

Understanding the variability of residuals and isolating the factors that cause it could help to reveal the processes that result in residuals during forest fires. Specifically, estimates of variability can illustrate the probabilities of post-fire residual formation and the spatial biases and associations of variability may provide indirect clues to causes of residuals. If residual occurrence is not random and is spatially biased to any factors, such as fire intensity, forest cover, site type, or terrain, then it can be hypothesized that those factors, directly or indirectly, represent causal factors of residual formation.

In contrast to the lack of direct information on causal mechanisms of post-fire residuals, the published literature does contain references to associations of residual occurrence with environmental factors, but the degree of rigour in formulating these associations varies, from *post hoc* observations (most common) to *a priori* hypotheses testing (rare). However, this evidence is all that is available to provide insight into causal factors of post-fire residuals.

Many factors can cause spatial biases in residual occurrence, and they are related to the scale of observation. Moreover, these factors can cause biases in post-fire residuals directly or interact with other factors. To reduce this complexity, we adopted a parsimonious approach to listing and ordering factors reported in published literature that cause spatial associations. Understanding spatial variability is important to develop policy related to emulating natural disturbance as well as to put it into practice. Therefore, we considered the perspective of a forest manager who would apply the knowledge of post-fire residual occurrence to emulate natural disturbance patterns and the relative reliability of spatial information readily available to do so. Beyond being a template to organize published information, these factors, in the order given below, also provide an additive null model for explaining spatial associations of post-fire residual occurrence for research.

While there are many two-way and multi-way interactions among causal factors of residuals, our choice of a model that is parsimonious and relevant to the perspective of a forest manager is:

> Probability of residual occurrence = f {pre-burn forest cover, site conditions and terrain, proximity to water bodies, fire event geometry and behaviour, other sources and random variability}

where we use pre-burn forest cover to mean life form and species composition; site conditions includes moisture regime and soil; and terrain includes slope and aspect. Water bodies includes only permanent streams and lakes. Fire event geometry refers to size and shape of fire event. Fire behaviour includes intensity and fire weather. However, we recognize that these factors are not independent.

This model explains not only the occurrence of different categories of residuals, especially the patches and live trees, but also the relative abundance of these residuals. Below we summarize the information on post-fire residual associations available in the literature in relation to the model by residual category.

Spatial association with pre-burn forest cover characteristics

Residual patches

Many published reports included information that supports pre-burn forest cover composition as an important explanatory variable for residual patch occurrence (Smyth 1999, Kafka et al. 2001, Epting and Verbyla 2005). However, some authors cautioned that the relative influence of forest composition varies from fire to fire (Smyth 1999) with stand age and site conditions (Kafka et al. 2001). Generally, relatively higher extents of post-fire residual patches are evident in pre-burn cover types of lowland conifer than upland conifer (Kafka et al. 2001, Epting and Verbyla 2005). According to Epting and Verbyla (2005), hardwood cover types such as aspen and birch may have high residual extents due to their low flammability and lack of crown fuel ladder, in comparison with spruce forests, which have a fuel-rich understory. All these reports appear to allude the post-fire residual patch-forest cover type spatial association to how fire avoided certain cover types, rather than how those cover types survived fire.

Residual trees

Association of variability in tree survival post-fire is often related to characteristics of the species that dominate a cover type. For example, balsam poplar is reported as the most fire-resistant boreal tree species due to its bark thickness, followed by jack pine, black spruce, and aspen (Lutz 1956, Scotter 1972). The degree of survival in conifer trees after fires vary among reports, but is generally considered to be higher than for deciduous species (Hobson and Schieck 1999), especially when the conifer trees are larger (Ohman and Grigal 1979, Hauessler and Bergeron 2004). Exceptions seem to be upland spruce, white spruce (*Picea glauca* (Moench) Voss), and jack pine, which can have low post-fire survival rates (Lutz 1956, Scotter 1972). Scotter (1972) states the low survival of white spruce is due to its thin bark, shallow roots, and low branches. Hardwood cover types, except balsam poplar (*Populus balsamifera* L.) as mentioned above, generally produce few or no live tree residuals. White birch (*Betula papyrifera* Marsh.) does not survive readily due to its thin bark when young and even with thicker bark when older still does not survive due to high flammability of the peeling bark (Lutz 1956, Scotter 1972). Aspen has thick but fissured bark and therefore is less likely to survive for more than a year after fire (Hely et al. 2003). Aspen tree residuals may occur at the fire edge, especially if they are large, but not in the fire interior (Haeussler and Bergeron 2004). Conifer-hardwood mixed cover types could contain more live tree residuals than pure stands of jack pine or aspen (Morissette et al. 2002).

Smaller trees, with relatively smaller diameters, shorter heights, and lower crown bases, have the lowest survival rate (Kafka et al. 2001, Beverley and Martell 2003, Hely et al. 2003). While survival rates can vary based on individual species and fire intensity, in general, trees larger than 10

cm diameter are more likely to survive (Beverley and Martell 2003). For example, both white pine and red pine trees usually survive fire when they are mature (Apfelbaum and Haney 1986).

Residual snags

Generally, snag abundance is a direct result of the pre-fire density of trees, as observed in cover types of black spruce (Graf et al. 2000), jack pine and black spruce (Sander 2003), aspen (Lee and Crites 1999b), and mixedwood (Hansen 1983). Only one comparison of pre-burn cover types with respect to residual snag densities has been reported, and it showed that black spruce had more snags than jack pine-black spruce mixed stands (Miyanishi and Johnson 2002). However, these differences in residual snag abundance among cover types are a reflection of stand age and stem density and are difficult to generalize. Stand age is another important source of variability that determines the percentage of snags created by fire (Apfelbaum and Haney 1986). It has been suggested that post-fire snag densities in aspen stands may reflect pre-fire stand densities (Lee and Crites 1999).

Downed wood

In the only report with information about the relationship between post-fire downed wood abundance and forest cover, downed wood was found to be more abundant in aspen than in mixedwood and jack pine cover types (Morissette et al. 2002).

Spatial association with site conditions and terrain

Residual patches

In general, post-fire residual patches are positively associated with areas of high moisture regime, such as wet areas and lowlands (Quirk and Sykes 1971, Thomas 1998, Arsenault 2001, Nowak et al. 2002, Rees and Juday 2002). One common observation in literature is that fires skip most wetlands and other moist areas and leave unburned islands (Quirk and Sykes 1971, Thomas 1998, Nowak et al. 2002, Rees and Juday 2002). Arsenault (2001) found that post-fire residual forest cover occurred mostly at margins of peatlands. Low-lying areas such as depressions (Buech et al. 1977) and swales (Nowak et al. 2002, Rees and Juday 2002) act as fire barriers because they are moist and thus help to create more residual patches (Thomas et al. 1998). Furthermore, the proportion of area burned can vary with the relative moisture regime. For example Thomas et al. (1998) found that generally less area burned on till than on bedrock. As well, on organic deposits, conifer stands are less subject to crown fire and therefore more likely to remain as residual patches (Kafka et al. 2001).

Residual trees

Areas with a higher moisture regime, such as wetlands, lower slopes, and those that are poorly drained, have the highest occurrence of post-fire residual trees (Lutz 1956, Scotter 1972, Nordin and Grigal 1975, Apfelbaum and Haney 1981, 1986). Residual tree occurrence is least likely in well-drained areas with a lower moisture regime (Lutz 1956, Scotter 1972). Many others (Scotter 1972, Viereck and Dyrness 1979, Apfelbaum and Haney 1981, 1986) also observed that live tree residuals occur mostly in black spruce bogs; on upland sites residuals tend to occur only when the trees are large. In general, conifer trees growing on organic soils are more likely to survive than those growing on till and bedrock, but non-conifers survive even on till and bedrock (Kafka et al. 2001).

Residual snags

Reports on the associations of post-fire residual snags with site conditions appear to vary. For example, Bond-Lamberty et al. (2003) observed that snag abundance was higher on well-drained boreal black spruce sites than on poorly drained sites. However, Le Goff and Sirois (2004) observed the reverse: Residual snag density was greater on poorly drained than on well-drained sites. Others have reported that spatial variability in site conditions can cause variability in occurrence of residual snags in general, even though they did not provide specifics about those associations (Apfelbaum and Haney 1986, Lee and Crites 1999, Harper et al. 2005).

Downed wood

Occurrence of downed wood residuals is considered to vary with site productivity (Harper et al. 2005). For example, some have observed that greater downed wood residual volume is associated with well-drained sites compared to poorly drained sites (Bond-Lamberty et al. 2003). Also, Harper et al. (2003) observed coarse or clay sites have more residual downed wood than organic sites do. These differences among site conditions may exist because trees are generally larger on better sites (Bond-Lamberty et al. 2003).

Spatial association with proximity to water bodies

Residual patches

Generally, post-fire residual patches are considered to be positively associated with open water bodies as well as streams (Larsen 1962, Thomas 1998, Kafka et al. 2001, Lee and Smyth 2003). Kafka et al. (2001) found that most islands of residual patches within fires were near open water bodies and Larsen (1962) found the same to be true for peninsular residuals. Furthermore, residual patches occur most commonly on the leeward side of lakes (Thomas 1998). Lee and Smyth (2003) found that nearly half of the variability in residual patches was associated with proximity to streams inside the fire they studied. That spatial association was strongest with larger permanent streams and weakest with small intermittent streams. They also found that the area of residual patches decreased with distance to permanent streams.

Residual trees

The published literature presents no information on associations of post-fire residual trees with proximity to water bodies.

Residual snags

The published literature presents no information on associations of post-fire residual snags with proximity to water bodies.

Downed wood

The published literature presents no information on associations of post-fire residual downed wood with proximity to water bodies.

Spatial association with fire event geometry and behaviour

Fire event geometry

Residual patches

The extent and size of residual patches appear to vary with fire size. Eberhardt and Woodard (1987) reported that small fires (20-40 ha) did not have residual islands and that the median residual patch size increased as fire sizes increased from 400 to 20,000 ha. However, they also noted that the density of residual patches (i.e., number per 100 ha of fire area) decreased as fire sizes increased. Eberhardt and Woodard (1987) also mentioned that the internal distribution of residual vegetation varies significantly with fire size, and residual patches within fires may be spatially autocorrelated. For example, in the 69 fires they studied, the extent of residual patches decreased as the distance to neighbour residual patches increased (from 100 m to 500 m) indicating a high degree of spatial clustering of residual patch occurrence.

Larger fires may have more internal heterogeneity in forest cover, terrain, and site conditions and therefore produce more variability in residual patches. For example, larger fires present more opportunities for down-wind fire breaks, thus increasing the probability for occurrence of larger residual patches (Eberhardt and Woodard 1987). As Epting and Verbyla (2005) showed, broadleaf forest and shrub stands may act as landscape-scale barriers to fire spread, likely due to their lower flammability and lack of a crown fuel ladder. Furthermore, geological features (elongated drumlinoid ridges), certain cover types (spruce-dominated forests), and moisture regime (numerous lowlands and bogs) serve as natural fire breaks inside fires (Thomas 1998). Spatial adjacency of pre-burn cover types within fires may also be important in forming residual patches because of the juxtaposition of their relative flammability. For example, Simard et al. (1983) reported that inherently less flammable cover types such as hardwood may form few residual patches (or trees) if they are adjacent to highly flammable cover types such as jack pine.

Residual trees

Residual trees are more likely to occur near the fire perimeter (Lutz 1956, Harper et al. 2004) Density of live tree residuals decreases rapidly with the distance from the fire's edge, for example, Harper et al. (2004) reported a 90% decrease in tree residuals within 50 m inside the fire. Residual tree occurrence also may be high in the fire flanks and areas of night spread inside fires (Methven et al. 1975). According to Haeussler and Bergeron (2004), more aspen tree residuals occur at the fire edge than in the fire interior.

Residual snags

The published literature presents no information on associations of post-fire residual snags with fire event geometry.

Downed wood

The only report that associates residual downed wood with fire geometry indicates that the amount of residual downed wood did not change within 50 m of the fire perimeter (Harper et al. 2004).

Fire behaviour

Residual patches

As Thomas (1998) observed, occurrence of residual patches is closely associated with spatial fire behaviour and therefore can be used as an indicator of fire intensity within a fire event. For example, fire weather, especially wind-induced changes in fire behaviour such as horizontal roll vertices, creates radially concentric narrow strips of residual patches (Arsenault 2001). This effect is also evident from the finding that low nighttime fire intensities result in high incidence of residual patch formation (Simard et al. 1983). Epting and Verbyla (2005) suggested that variation in residual patch patterns within fires may be due to differences in fire behaviour caused by changes in fuel moisture content. Also, fires that burn for long periods may produce high variability in residual patch occurrence because weather conditions and therefore fire behaviour vary more (Kafka et al. 2001). Changes in fire behaviour due to neighbourhood effects, such as proximity to flammable fuel, also cause variability in residual patch occurrence (Simard et al. 1983).

Residual trees

Fire intensity is often reported as being important in determining live tree residual occurrence (Lutz 1956, van Wagner 1973, Methven et al. 1975, Ohman and Grigal 1979, Morissette et al. 2002, Hely et al. 2003, Haeussler and Bergeron 2004). Probability for occurrence of live tree residuals is considered to be highest where fire intensity is lower, such as along fire perimeters (Lutz 1956, Harper et al. 2004, Haeussler and Bergeron 2004) and in partially burned areas (Morissette et al. 2002). Changes in fire intensity within fires due to diurnal shifts in wind speed, heterogeneous topography, and location inside the fire may influence tree survival (Methven et al. 1975, Hely et al. 2003). Differences in fuel availability, based on differences in cover types, also change fire intensities spatially (Lutz 1956, Morissette et al. 2002), thereby changing the spatial probability of occurrence of live tree residuals. Differences in species' response to a given fire intensity (e.g., van Wagner 1973, Ohman and Grigal 1979) is another important factor in determining spatial association of residual tree occurrence with fire behaviour.

Residual snags

Sander (2003) suggested that fire intensity is an important parameter in explaining the variability in reported ranges of snags in boreal forests. Apfelbaum and Haney (1986) indicated that lower fire intensities will cause less tree mortality and therefore result in fewer residual snags.

Downed wood

The published literature presents no information on associations of post-fire residual downed wood with fire behaviour.

Temporal patterns in residuals

Why is it important to understand temporal patterns?

Although temporal changes in residuals are not specifically discussed in Ontario's NDPE guide, we know that residuals that forest fires leave in the form of live tree patches, individual live trees, snags, and downed wood are not static. Most published reports focus on post-fire residuals in the period immediately after fire, even though post-fire residuals are transient, both in the short and long term. Their spatial patterns, occurrence, and extents change over time. As well, they may shift among residual categories. For example, over time, a residual patch may become a scattered group of snags with intermittent residual live trees due to delayed mortality, or residual trees and may fall over and become downed wood. Moreover, disturbances after fire, such as windthrow and pest infestations, may change the residual patterns. These changes could be rapid, due to an episodic event such as storm-related windthrow of all live residual trees, or gradual, as trees age, decay, break, and fall over. Such changes over time represent the net result of many interacting factors, such as the nature of the fire disturbance that caused the residuals, the tree species autecology, local site conditions, weather patterns, and residual spatial patterns.

While it may be onerous to identify temporal trends of residuals and the exact causal factors of such changes, it is important to recognize that residuals do change over time. Below we review the published literature on temporal changes in residuals, based on the perspective of forest managers who wish to emulate post-fire residual structure, by considering the longevity of various types of residuals: live tree patches, individual live trees, and snags. We did not review decomposition changes in downed wood residuals.

Longevity of post-fire residuals

Residual patches

The only information in published literature on longevity and temporal changes of residual patches was provided by Arsenault (2001). He studied a fire-driven landscape in boreal Quebec and found that evidence of residual patch formation and original spatial patterns remained even four decades after fire.

Residual trees

Delayed mortality rate of live tree residuals may differ among species (Ohmann and Grigal 1979, Hely et al. 2003) but the expected survival period is less than five years (Ohmann and Grigal 1979, Viereck and Dyrness 1979, Hely et al. 2003, Stambaugh 2003, Lavoie 2004). Hely et al. (2003) found that the mortality rate of live tree residuals during the period of three to 16 weeks after fire varied among species but was highest in aspen, followed by black spruce and jack pine. Haeussler and Bergeron (2004) also found that very few live tree residuals remained in an aspen forest three years after the fire. Even where fire intensity is low, such as in lightly burned lower-slope black spruce stands, most live tree residuals may die within three years (Viereck and Dyrness 1979). Reports of windthrow in live tree residuals are rare, except Apfelbaum and Haney (1981) who noted many live tree residuals were windthrown within one year after fire, especially in and around bogs.

Residual snags

Changes in residual snags appear to occur more slowly than those in live tree residuals. Based mostly on observations and chronosequence studies, only few snags appear to fall and become

downed wood within the first three to five years after fire (Ohman and Grigal 1979, Viereck and Dyrness 1979, Apfelbaum and Haney 1981, Hansen 1983, Lee and Crites 1999, Nalder and Wein 1999). There is considerable evidence that most snags fall between five and 15 years of the fire (Hobson and Schieck 1999, Schaeffer and Pruitt 1991, Sander 2003, Awada et al. 2004, Capar 2004, LeGoff and Sirois 2004). Only a few snags are left standing after 20 years, and they are usually very few, large stems, and are widely spaced (Lavoie 2004). Residual snag densities increase in time as live tree residuals continue to die (Viereck and Dyrness 1979, Stepnisky 2003, Stambaugh 2003). The rates of snag fall seem to vary with site conditions and species. Lutz (1956) noted that windthrow of black spruce snags occurs especially on shallower soils due to root kill. However, residual snag density decreased only slightly in heavily burned black spruce even on a ridge top (Viereck and Dyrness 1979). In some instances, all aspen snags may fall within five years (Nalder and Wein 1999), while less than half of jack pine and spruce snags may fall (Schaeffer and Pruitt 1991). However, few jack pine and black spruce snags remain standing 10 years post-fire (Schaeffer and Pruitt 1991, Nalder and Wein 1999). The same is true for white spruce (Awada et al. 2004) and mixedwood snags (Apfelbaum and Haney 1986); most fall within 15 years of the fire. However, snag breakdown may continue for several decades for aspen, jack pine, and black spruce (Sander 2003).

CONCLUSIONS

In this section we synthesize the information found in the published literature to summarize the state of knowledge of post-fire residuals. First, we present an *assessment of what is known*, followed by a set of *hypotheses of residual formation* and causal factors that govern residual abundance and variability. Finally, we provide a *synopsis of the published knowledge in relation to specific directions in the NDPE guide*.

Conclusions – What is the overall state of knowledge?

What are residuals? Are they described and defined consistently?

Post-fire residuals are commonly described by four standard categories: patches, individual live trees, snags, and downed wood. *Patch* is always used to denote island (insular) residual clusters, and separation of insular and peninsular patches in the literature is very rare. As well, the minimum number of trees, their proximity and spread, and the degree of greenness required before they are grouped as a patch are rarely defined. Live tree residuals are described broadly as live trees and snags as dead trees. Descriptions of downed wood vary widely depending on the specific study objectives – from wildlife habitat to carbon sequestration values. Overall, no universal definition of *residuals* exists in the literature and the concept that residuals are a continuum from patches to trees is rarely acknowledged.

For the most part, the functional formation of residuals, i.e., how they came to exist, is not considered in definitions or descriptions of residuals in the published literature. Nor are the definitions necessarily related to the potential function of residuals. As a result, the terms used to describe residuals vary widely and often these terms are not defined. When they are, the definitions are not consistent and rarely are the definitions used in one publication compared with those used in others. Definitions provided are a combination of qualitative and, less frequently, quantitative descriptions. As well, these quantitative descriptions are a mixture of metrics that often are not comparable. Metric categories, such as patch sizes, tree diameter, and downed wood size, also vary widely, often arbitrarily, with little rationale provided for truncations of categories and minimum sizes used to measure abundance.

How much is left behind? Abundance and variability of residuals

The most prevalent information about residuals in the published literature is abundance estimates. The extent and sizes of post-fire residual patches, live tree density, snag density, and the amount of downed wood vary widely among reports. Insular residual patch extent varies from none to over 20% of fire area and mean patch sizes range from 2 ha to over 40 ha. Live tree abundance reports range from no trees per ha to over 600 trees per hectare and the snag abundance reports vary from 50 stems per hectare to nearly 2,500 stems per hectare. Downed wood volumes reported in burned areas vary from 60 m^3 per hectare to 300 m^3 per hectare, and downed wood as a percentage of ground cover varies from 0.2% to 43%.

However, as mentioned above, it is difficult to compare or generalize these estimates because of unclear or inconsistent definitions of residuals, differences in the metrics used to report abundance estimates, and the variety of size categories used to quantify them. Comparisons are made even

more difficult by inadequacies in documenting important information such as behaviour of the fires that caused residuals; the pre-burn cover composition, age, and other characteristics; and site conditions such as soil, terrain, and moisture regime. Abundance estimates are commonly grouped by forest cover types for patches and by species for trees. Generally, snag and downed wood abundance estimates are not differentiated by species. Another logical grouping absent from the literature is the temporal origin of snags and downed wood, i.e., snags and downed wood that pre-date fire are usually included in post-fire residual abundance estimates. In most cases, observations of residuals are based on one or few fires, and as a result within- and among fire variability in residual abundance are not commonly reported. Even when it is reported, variability is rarely attributed to sources such as forest type, geography, age, or time since disturbance with any rigour.

What are the spatial biases and patterns in occurrence and abundance of residuals?

Reports of attempts to associate post-fire residual structure with other factors to explain their occurrence and spatial variability are infrequent in the literature. Even when associations are reported and discussed, these are often based on ad hoc observations rather than results of data analyses. Here we mention only those associations that recur in reports and only when some generalities could be extracted from these observations.

For residual patches, some of the reported spatial biases and patterns include the relationship between residual patch occurrence and forest cover type. This relationship was ascribed to relative flammability and probability of crown fires in cover types as linked to site. For example, most reports associate residual patch occurrence with wet areas, lowlands, and proximity to water bodies. As well, residual patch size is considered to be correlated with fire size, because in larger fires the probability for fuel breaks is higher, creating patches in fire skips. However, some consider larger fires to have proportionately less residual area because fire intensity is higher and thus fewer areas will be skipped.

Overall, it appears that live tree residual occurrence is associated with certain combinations of cover type and fire behaviour. Live tree residuals are more likely, for example, in conifer than deciduous cover types, in wetter areas, and for larger diameter stems. They are also more likely to occur near the fire perimeter, in night spread areas, and at the fire flanks where fire intensity is lower. Snag occurrence is reported to be associated with pre-fire stand density and cover type, and possibly stand age; the latter may be a function of stem size and density. No associations are reported in the literature for downed wood occurrence.

What happens to residuals? Temporal changes during the first decade and after

The published literature includes no reports of direct measurement of temporal changes to patches. However, based on studies assessing numbers and sizes of patches many years post-fire and those using a chronosequence approach, it appears that patches can persist for decades. If and how their characteristics, such as shape, size, and density, change over time remains unknown and undocumented.

Individual live trees can become snags or fall and become downed wood. In the literature, timing of the latter is not well quantified, but it appears that time to mortality for trees surviving fire may be species dependent. Since no reports directly measured fire intensity and forest cover linked to site conditions, post-fire tree mortality may not be solely species related. Information about how long it takes before snags become downed wood is based mostly on observations and chronosequence studies. Few snags appear to fall within 3 to 5 years after fire, with most falling between 5 and 15 years. However, there are reports of snags remaining standing even after 40 years. These fall rates may be species dependent but, as for live trees, this is uncertain.

What are the sources and quality of knowledge?

Superficially the published literature seems to contain much information about post-fire residuals. However, our examination of the literature revealed that is not so for several reasons. First, studies focused primarily and entirely on post-fire residuals are sparse, with most published reports focusing on residuals as a secondary objective. This has resulted in incomplete views and information on residuals. Second, the lack of standard definitions and terms used in various studies to describe and delineate post-fire residuals makes among-report comparisons and contrasts of findings difficult. Third, we found that much of the information in published reports provided is incomplete, with key aspects of methodology and descriptions of the study sites (fire, forest cover, and site conditions) missing. Thus, it is difficult to synthesize and generalize trends in post-fire residual occurrence and variability. Fourth, most reports provide estimates of residuals and other information from single study fires, with low sampling intensities, both in space and time. Therefore, reliable estimates of variability of residuals within and among fires are not common. Fifth, most published reports do not reference one another; each report typically is an isolated entity that is not linked to available knowledge and thus does not connect or advance the knowledge base. As a result, each study was approached differently making the information generated difficult to compare.

As well, very few report studies or results that involved hypothesis development and testing. For example, only two reports we reviewed had *a priori* hypotheses and only three reports provided post-hoc hypotheses based on general observations. Finally, a notable fraction of the documents we found during our search of post-fire residual literature are unpublished internal reports and incomplete drafts that are not accessible to general readership. While these contain potentially valuable information and insights, they cannot be considered as part of the published knowledge. Given the above, our overall conclusion is that the published literature on post-fire residual structure abundance and variability is incomplete, lacks rigour, and thus is not very reliable. However, the available information provides an excellent base for hypothesis development and testing in studies on post-fire residuals that are well designed and rigorous.

Conclusions – Overall hypothesis of residual formation and causal factors of abundance and variability

Post-fire residual formation can be simplified as the net result of sub-macro scale interaction of three components: forest cover, site conditions, and fire behaviour (Figure 6). It is sub-macro because the over-arching geoclimate acts as a macro-scale constraint by controlling these three factors. While these components and their two-way and three-way interactions are well studied and published in the fire behaviour and fire ecology literature, their relevance to residual formation is not well established, especially in the post-fire residual literature. Therefore, we propose the following abstraction of the residual formation process, and thus the factors that explain the abundance and variability of post-fire residuals. The first group of residuals are formed because fire avoids the forest cover, leaving patches where not only the overstory cover is intact but also the forest floor and understory remain unburned. These residual patches are structurally and functionally identical to pre-burn forest. The second group of residuals are formed when the forest cover, understory, and forest floor are burned but fire intensity is too low to reduce forest structure to ash. Depending on the fire behaviour, this group will contain live trees, snags, and downed wood. The live trees may be strongly spatially clustered (and may appear as patches but are not structurally or functionally identical to pre-burn forest) or interspersed with snags (and appear as individual live trees).

We suggest that residual patch formation results from meso-scale interaction between spatial patterns in fire event behaviour (as controlled by fire weather, wind, diurnal patterns, etc.) and fire barriers in the landscape (e.g., terrain, water bodies). These processes are more likely to explain spatially where fire will skip and avoid burning and also determine the size and shape of the residual patches formed. At low severities of fire weather, even areas that would not typically form fire barriers, such as forest cover with low flammability, may form residual patches. Therefore, an understanding of spatial formation of fire barriers at different fire weather severities may provide a guide to probability for residual patch extent, variability and spatial distribution in a landscape. Furthermore, we contend that formation of residual patches is spatially predictable *a priori* by knowing patterns of fire barriers in a forest landscape, and that this knowledge will be useful for applications such as developing forest policy and management practices for emulating natural disturbance patterns at meso-scale.

In contrast to the above, we suggest that residual formation at individual stem level as live trees is a function of relatively more complex micro-scale (nested within macro- and meso-scale) interactions of fire behaviour (e.g., eddies, local intensity), local 'site' conditions (moisture, terrain, etc), fuel condition (amount, nature, and flammability), and species tolerance to fire (e.g., bark thickness, ladder fuels). Individual live tree residuals and aggregates and clusters of live tree residuals interspersed with snags, are formed when local fire intensity is below the threshold that is required to kill the tree at canopy, stem and/or root level. While aspatial probabilities of residual of live tree occurrence as a function of forest cover and potential fire intensities may be understood, because of vagaries in spatial patterns fire intensity during a burn it will be difficult to understand the spatial probabilities. We contend that formation of residual live trees is relatively difficult to spatially predict *a priori* by knowing forest cover, site conditions, and even assumptions of overall fire behaviour. Therefore, applications of the knowledge of residual live tree formation in policy development and forest management may remain aspatial and at micro-scale. However, when the fire intensity is above the threshold for tree mortality, residual snags are formed. The abundance, spatial distribution, and variability of snags is a direct function of the pre-burn forest cover conditions such as stand density and spatial distribution and thus readily predicted *a priori*.

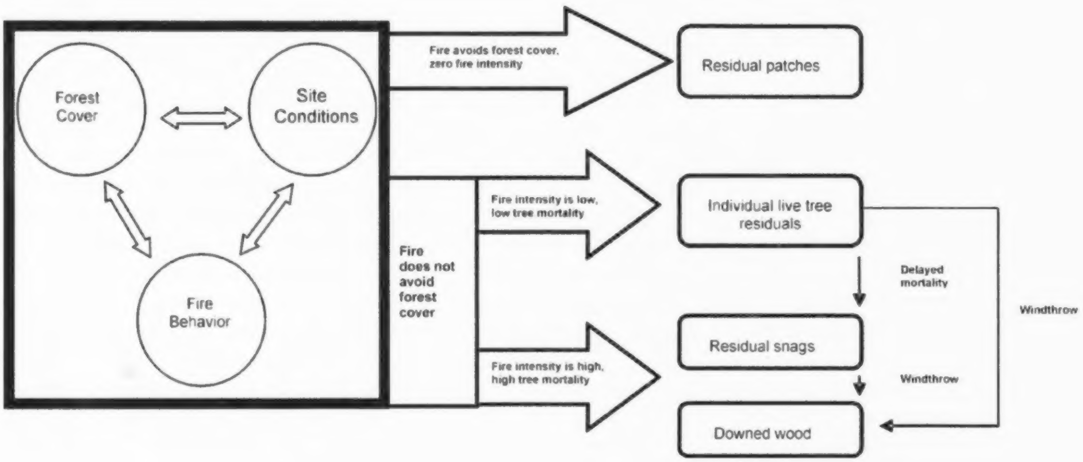


Figure 6. *A conceptual overview of residual formation during forest fires at patch and tree scale.*

Residuals thus formed during a fire are not constant in time. All types of residuals change with time since fire, primarily due to windthrow: live trees and snags may add to downed wood pool while residual patch shapes change and sizes decrease due to tree fall near the burn:residual interphase. Although the occurrence of macro- and micro-bursts in windstorms may be difficult to predict spatially, the relative wind firmness of residuals, and therefore the susceptibility for windthrow, may be predicted by site factors and tree species and stand characteristics. Another temporal change in residuals is the delayed mortality of trees, which increase the snag abundance over time. These changes may be predicted by species characteristics and spatial aspects of fire behaviour.

Conclusions – What is the state of knowledge in relation to NDPE guide?

Ontario's NDPE guide (OMNR 2001) provides directions for retaining residual structure in forest harvest areas to emulate fire disturbance patterns. These directions include guidance for retaining insular and peninsular residual patches, individual live trees and snags, and downed woody debris. Here we summarize the state of the published knowledge to assess the uncertainties and gaps in relation to the specific directions in the guide (cited below in italics) by residual category.

Guidelines for residual patch retention

Insular residual patch retention

- *range of 2 to 8% of planned disturbance area based on forest cover type (**guideline**)*

  These directions are within the range (0 - >20%) of insular patch extent reported in fire events in literature. However, insular patch extent varies within fires (for example, due to variability in site, cover type, and fire geometry) as well as among fires (for example, due to fire size and geographies). It is difficult to assess the exact percent likelihood of residual patches in individual forest cover types proposed in the NDPE guide, because the composition of residual patches is not commonly reported in the literature. However, the reports of residual patch composition agree with the general continuum in the NDPE guide.

- *minimum patch size – .25 hectare*

  The range (0.1 - > 1 ha) of minimum size reported for post-fire residual patches in the literature encompasses the guide direction. However, this truncation is arbitrary with no rationale provided in the literature.

- *well distributed within cutover subject to how fire would naturally distribute (**standard**)*

  All reports agree that residual patch location vary within fires based on fire behaviour as affected by forest cover, soil moisture regime, and terrain. More residuals patches are reported in areas which form barriers for fire spread such as those with high moisture regime, on lee side of lakes, and near large streams; and in areas of slow fire spread. It is also suggested that fires in more heterogeneous landscapes produce higher variability in residual patches.

- *not available for subsequent harvest (**standard**)*

  One report indicates that longevity of post-fire residual patches is more than four decades. No other information was found in literature to indicate shorter residual patch longevity.

While there is evidence in the literature to support the NDPE guide directions for insular residual patch retention, there is considerable uncertainty in this knowledge, especially with respect to variability and association of residual patches. This is mainly due to inconsistencies and arbitrariness in study methods and observation-based inferences (as opposed to rigorous analyses and hypothesis testing).

Peninsular residual patch retention

- *range of 8 to 28% of planned disturbance area based on forest cover type (**guideline**)*

  The only report that specifically identified peninsular patches showed a range of 7–29% for peninsular residual patch area, which is close to the range in the guide directions.

- *well distributed around edge of cutover subject to how fire would naturally distribute (**standard**)*

- *50% of peninsular residual patch area is available for subsequent harvest after 3 metre Free to Grow greenup (**standard**)*

- *alternatively, a one pass harvest may include the removal of 50% of the volume in 50% of the exterior edge of the peninsular area leaving the core area unharvested (**standard**)*

  The published literature presented no information on post-fire peninsular patches relevant to the above directions.

The post-fire residual literature rarely referred to peninsular residual patches. Thus, the uncertainty in the knowledge of definition, extent, and variability of peninsular residuals is very high.

Guidelines for residual live tree and snag retention

Individual residual live trees and snags

- *retain species based on fire tolerance, silvicultural requirements and wildlife habitat value (**guideline**)*

  The fire tolerance ranking for species of residual live trees reported in the published literature generally agreed with that provided in the NDPE guide. However, aspen (poplar) and white birch fire tolerance were ranked lower in most published reports than they are in the NDPE guide.

- *retain 25 well spaced trees/ha (minimum average) at least 6 large diameter, live, existing (or potential) high quality cavity trees (**standard**)*

  The maximum range of post-fire residual live trees (>600 per ha) reported in the literature far exceeded that specified in the guide directions. However, many reports described forest fires that produced no residual live trees. Reported post-fire snag densities varied widely (57- 2,400 per ha) and also far exceeded guide directions. While not specified in most reports, larger trees may survive fire more often than smaller trees do. The literature did not address the spatial distribution of live tree and snag residuals post-fire other than presenting associations with high moisture regime, fire geometry, and fire behaviour.

- *range of tree species, diameters and condition (snags to healthy trees) to be left based on species (**guideline**)*

  All published reports that addressed post-fire residual live trees and snags indicated that species and diameters of residuals varied widely.

Although the literature addressed abundance values of post-fire residual live trees and snags, generalizing this knowledge is difficult due to missing information on pre-burn stand conditions (cover type, age, size), fire characteristics, time since fire, and site variables. Reported attempts to associate residual trees and snags with site, stand, and fire variables were mostly post-hoc observations. Therefore, published information relevant to these NDPE guide directions is highly uncertain.

Guidelines for downed wood retention

Downed woody debris

• *provide coarse downed woody debris through: using cut to length or tree length harvest systems; individual tree and snag retention; leaving unmerchantable logs on site; redistribution of roadside slash/chipping waste and avoid windrowing of coarse wood debris during mechanical site preparation (**guideline**)*

• *provide fine woody debris on shallow or very shallow or very coarse textured soils through: avoiding full-tree harvesting on these sites and redistribution of logging slash after roadside delimbing or chipping (**guideline**)*

Published reports of post-fire downed wood abundance estimates and their variability differ considerably. Relating the published information about post-fire downed wood to the guide direction is difficult because the direction is very general.

Conclusions – Summary

Overall, the state of published knowledge is relatively rich in estimates of abundance and extent of post-fire residuals. However, because the standards in defining and quantifying residuals are inconsistent and sometimes ambiguous it is difficult to synthesize and generalize this information. Furthermore, most reports lack complete information on methods and results that are critical to determine general patterns and trends in residuals. Therefore, the knowledge about causal mechanisms, spatial associations, and temporal changes of all residual categories is uncertain. While this is the largest gap in published knowledge of post-fire residuals, it is also the area of scientific knowledge most required for translating broad forest policies for emulating natural disturbances into specific forest management directions and practices, as in the *Forest Management Guide for Emulating Natural Disturbance Patterns*.

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Appendix I. List of *a priori* questions used to guide the literature review

1. What are residuals – how described? Residual are reported in many different ways.

   a. Descriptions and definitions in literature - qualitative and quantitative: There is no universal definition of "residuals", e.g., NDPE guide is just one. Compare and contrast those provided in literature and generate broad base of terms and definitions; Do these differ by forest type, geography, other? How do "structural legacies" differ from "residuals"?

   b. Structural categories: Post-fire residuals are a continuum, subjectively categorized (user defined) in the literature. Are these definitions a function of (a) pre-burn stand density (e.g., relative amount of snags) or (b) post-burn proportion of live:snag for patches? Is minimum live tree density factored into live tree patch definitions?

      i. Large live tree patches: Are these reported? And if so, how defined and in what context?

      ii. Small live tree patches: Are these reported? And if so, how defined and in what context? How different from large live tree and individual live tree?

      iii. Individual live trees: How defined? Any mention of degree of damage, i.e., how differs from snag in time (temporal dimension to definition)?

      iv. Tree snags: How defined? Any subcategories by size of stems or by patterns in occurrence (clumping vs. single trees)? Is there a temporal dimension to definition?

      v. Downed wood: How defined? Is downed wood from previous disturbances differentiated from that from current disturbance?

   c. Composition: Residuals can be sub/cross-categorized (as per below and other ways) – captures the variability and complexity of residuals and hints of causal factors and processes of residuals here.

      i. Species groupings – flammability and bark thickness: Any indication to group residuals by tree autecological characteristics? Which characteristics? Any attempts to categorize residuals by species groupings?

      ii. Diameter/size classes: Any indication/attempts of grouping residuals by tree diameter/size class?

      iii. Age classes: Any indication/attempts to group residuals by tree/stand age classes?

      iv. Density classes: Any evidence of attempts to define by post-burn structural densities (in any class)?

      v. Seral stage: Any evidence of attempts to define by seral stage of post-burn structure?

   d. Degree of fire damage: Residuals are referred to as binary (dead/live), but the live category can result in several ways (as below); dead category is a function of time.

      i. Escapees (fire didn't get there): Are these reported?

      ii. Tolerants (fire went through – no effect): Are these reported?

      iii. Survivors (burned, some damage but didn't die): Are these reported? Is a timeframe provided?

      iv. Dead: when did they die (relative to disturbance)?

2. How much is left behind – abundance and variability of residuals? Literature on residuals varies in estimates of abundance and variability.

   a. Abundance estimates by categories: How expressed? Dimensions (mass, numbers, volume, etc.) used to describe? What numbers are reported?

b. Within- and among fire variability by different sources: Is this commonly reported? How expressed, i.e., explicitly? What are the sources (forest type, geography, age, time since disturbance, etc.? What numbers are reported?

3. Where do they occur – spatial biases (both positive and negative) and patterns in occurrence and abundance? Space is a source of variability as well as a source of bias (non-randomness) in residuals; many spatial attributes may explain occurrence and abundance within a given fire (i.e., response patterns).

a. Peninsular vs. insular: Are these differentiated re: live tree patches? And if so how defined? Estimates of amount and variability?

b. Edge-to-centre transect in burn patches and centre-outward gradient in residual patches: Is there a gradient in residuals, and if so, is it important? How is edge defined (i.e., feathered or discrete)? Does it influence residuals?

c. Biases to terrain (e.g., drainage, aspect, slope position): What are the variables? Estimates of amount and variability?

d. Biases to fire disturbance characteristics (e.g., fire size, intensity, direction): What are the variables? Estimates of amount and variability?

e. Biases to soil/geology: What are the variables? Estimates of amount and variability?

f. Spatial distribution – clumping, random, etc: Is the within-fire spatial variability (i.e., not attributed to any particular source, which is more statistical/geometric than mechanistic) reported?

g. Spatial association with cover types: Any biases to, e.g., water bodies, bogs, past burns, cutovers, and other high/low flammable areas?

h. Other

4. Why are residuals there – causal factors? Residual occurrence and abundance are biased and can be explained by many factors. Are these commonly recognized in literature on residuals? If not, do other bodies of knowledge provide adequate information to understand variability?

a. Fire behaviour: Abundant literature on fire behaviour. Can specific attributes of fire behaviour be used to explain residuals?

i. Intensity: Intensity varies within and among fires – how does it affect residuals? Do different intensity zones (spatial) and periods (daily fire weather changes) result in different abundances in residuals? Is this confounded by fire spread rate (i.e., faster-moving, high-intensity fires creating more residual structure than slow-moving fires of same intensity – evidence from forest floor)? Are there threshold values of intensity that override the influence of other factors? Are there any interactions in effects of intensity with other factors (below)? Does fire intensity nest all other factors (below)?

ii. Fire season: Does the season of fire affect the residuals? Do spring fires produce residuals different than fall fires? What is the effect of leaf-on and leaf-off on residuals?

iii. Fuel: How does different quality/quantity of fuel influence residuals? Is this influenced by forest cover type or understory? How do crown fires influence residuals relative to ground fires (i.e., ladder fuel)? Any evidence that crown fires burn downwards to burn the tree tops but leave ground-level unaffected?

iv. Neighbourhood effects: How does spatial juxtaposition to different cover types, age classes, previous disturbances, non-forested areas, lakes (any effect of size relative to size of fire?), beaver ponds, roads, etc., affect post-fire residuals? When do/not riparian forests burn?

v. Distance from disturbance perimeter: Is there a concentric gradient inwards (i.e., fire intensity gradient)?

vi. Distance from residual patch perimeter (or centroid): Is there a concentric gradient outwards in live tree residuals?

vii. Other

b. Site conditions: Abundant literature on effect of site conditions on fire behaviour. Can this literature be used to explain effects of site conditions on residuals?

i. Terrain: Do slope, slope position and aspect affect residuals? If so, how? E.g., what is the effect of exposed vs. sheltered ridge positions?

ii. Moisture regime: Do differences in moisture regime explain residual occurrence and variability?

iii. Soil/geology: What aspects of pedalogical characteristics affect residuals?

c. Forest cover type: Abundant literature on fire ecology and autecology of forest cover types. Can specific attributes of autecology and stand dynamics be used to explain residuals? Are they independent, nested, or do they interact with others?

i. Survival mechanisms: Do differences in crown, branching patterns, root depth, bark thickness, etc., of different cover types affect residuals? Any evidence of aspen being predominant survivor (single live trees)? Is this true for patches as well?

ii. Age: Is there an effect of stand age on residuals? If so, what is the nature of that effect? Can it be generalized or does the effect of age depend on other factors above and below?

iii. Density: Is there an effect of stand density on residuals? If so, what is the nature of that effect? Can it be generalized or does the effect of density depend on other factors above and below?

iv. Height: Is there an effect of tree height (by species) on occurrence of crown fires (i.e., ladder fuels)?

5. What happens to residuals – temporal changes during the first decade and after? Residuals change with time since fire: Are these changes noticeable within 10 years of fire or delayed? Until when? Are these changes well documented?

a. Longevity of structure: How long do the post-fire residuals persist? Are changes evident within 10 years? Is this affected by density? Which categories of residuals undergo more changes? Are there any other factors (below) that interact with time effect? Any descriptions of changes in (or categories of) live tree residuals and snags through time (crown, no crown, stem breakage, etc.)?

b. Post-fire disturbances (wind, pests): What post-fire disturbances can affect longevity of residuals? If they do, is it known what those effects are?

c. Composition: Are there any noticeable compositional changes in residual patches? Do residuals of different species change with time differently?

d. Site conditions: Are there any effects of site conditions (e.g., terrain, moisture regime) on the longevity of residuals? If so, is it known what those effects are?

e. Other

Appendix II. Keyword list used for post-fire residual structure literature review

Residual stand structure/area	Forest type/Geographic location	Disturbance type
biological legac*	boreal	burn*
boundar*	conifer*	fire*
clump*	Great Lakes	postburn
coarse woody debris	jack pine	post-burn
corridor*	northern forest*	post-fire
dead tree*	northern hardwood*	post-wildfire
dead wood, deadwood	northern temperate forest*	post-wild-fire
disturbance characteristics	taiga	pyrogenic
downed wood	upland spruce	wild-fire*
downed woody debris		wildfire*
ecological effects of fire		
edge*	Alaska	
fine woody debris	Alberta	
fire-skip*	Canada	
habitat trees	Labrador	
insular	Manitoba	
island area*	Michigan	
island*	Minnesota	
large woody debris	New Brunswick	
leave patch*	Newfoundland	
legac*	Nova Scotia	
life*boating	Ontario	
legacy trees	Quebec	
live	Saskatchewan	
matrix remnant*	Yukon	
patch*		
peninsula*		
refugia*		
remnant*		
reserves		
reserve trees		
residual formation*		
residual*		
severity		
single live trees		
skip*		
snag*		
stand		
standing dead		
stands		
stringer*		
structur*		
unburn*, un-burn*		
undisturbed		
veteran*, vets		
ecological effect*		
wildlife tree patch*		
retention		
stand development		
stand initiation		

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